P-S seismic exploration: A mid-term overview

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ABSTRACT

Three-component (3-C) seismic recording captures the seismic wavefield more completely than conventional techniques. It is thus useful for enhancing conventional P-wave imaging as well as for generating S-wave images. In the last several years, 3-C surveying has developed rapidly - often to create converted-wave (P-S) images. Largely conventional survey design and acquisition can be used for P-S recording. Some special processes for P-S analysis include anisotropic rotations, shear receiver statics, asymmetric binning, shifted hyperbolic velocity analysis, P-S to P-P transformation, P-S DMO, pre- and post-stack migration, and stacking velocity and reflectivity inversion for S velocities. Current P-S sections are approaching the quality of conventional P-P seismic data. Numerous applications for P-S sections have arisen including sand/shale differentiation, limestone/anhydrite/dolomite identification, definition of interfaces with low P-wave contrast, anisotropy analysis, imaging through gas zones, and reservoir monitoring. Converted-wave analysis holds great promise for marine surveys and land 3-D problems. Imaging through volcanic (or high-velocity) layers and in regions of significant structure also look promising. Development of the P-S method has taken about 10 years, but is now entering into its commercial phase and promises considerable usefulness.

BACKGROUND

The primary method in exploration geophysics remains P-wave reflection surveying. And for good reason: compressional waves arrive first, usually have high signal-to-noise values, have rectilinear motion, are easily generated by a variety of sources, and propagate in a marine environment. We expect that P-wave reflection surveying will be the dominant exploration method for some years to come. Case closed, but several questions are germane: Can we improve P-wave pictures? Can we generate complementary or augmenting images? When P-wave surveying fails, can we use other techniques? Perhaps the most straightforward answer to these questions is yes and try 3-C recording. There remains considerable work to do in using 3-C recordings to improve P-wave data. However, the thrust of this paper is to review the current state of converted-wave (P-S) seismic exploration.

Concentrated work in P-S analysis has been proceeding for about 10 years. We might compare this with the development of P-wave 3-D seismology. The 3-D seismic concept and early experimentation came about in the late 1960’s, theory and processing largely worked out in the ‘70’s, and application in the 80’s (the first contractor 3-D survey in Canada was in 1981) - about 20 years from concept to common practice. P-S surveying was proposed and tried in the early 1980’s with basic processing worked out in the late 1980’s to early 1990’s. Assuming P-S surveying is on a similar track as was conventional 3-D analysis, we would expect it to be common in the next several years.

If the broad goal of seismic exploration is to create a 3-D depth image of rock type, structure, and saturant then we will need all the information that is available through the seismic method. Again, we are unlikely to be able to do this with P waves alone. This is because different rocks and saturants have a similar P-wave response. S-wave properties along with the P-wave properties can help characterize the rock structure, type, and fluids therein. So how can we obtain S-wave properties?

We can attempt to find S-wave information via amplitude-versus-offset analysis (AVO) of P-P data. AVO is useful in some areas, but often limited elsewhere due to its somewhat indirect or second-order dependence of P-wave reflectivity on S-wave velocity. In addition, there are noise and processing problems with AVO analysis and perhaps even lack of a resolvable effect.

S-S surface seismic surveys are also possible and have been used. They directly measure S-wave values. Unfortunately, S-S seismic sections are often very noisy and have low resolution - largely because of a two-way propagation path as an S wave through the near surface. Furthermore S-wave sources are expensive and not applicable in some environments (e.g. marine settings, transition zones, muskeg, environmentally sensitive areas).

P-S surveys are a relatively inexpensive and effective way to obtain S-wave information. If we do have P-S reflectivity, what can it be used for?

- providing another section with independent properties (e.g., velocity, multiples, tuning)
- imaging interfaces with low P-wave contrast
- assisting P-P interpretation via Vp/Vs and additional sections
- augmenting conventional AVO analysis
- investigating anisotropy and fractures
- calibrating P-wave bright spots
- vector filtering and side-scanning
- using Vp/Vs for lithology
- imaging through gas chimneys from leaky gas reservoir
- monitoring reservoir changes

Let’s look at some of the tools that have been developed for S-wave work.

TOOLS OF THE TRADE

Elastic-wave logs

Full-waveform sonic logs give information about both P-wave and S-wave velocities (Mari et al., 1994). Transmitted tube waves from a monopole source, flexural waves from dipole sources, and screw modes from quadrupole sources can all be used to estimate the formation shear velocity under various conditions. Mari et al. (1994)

also discuss the use of reflected energy, sourced and recorded by a single tool, to determine the dip and maximum offset of reflectors near or intersecting the well. They use both P-P and P-S reflected events in the analysis.

The basis of much of the work in P-S exploration relates to anomalous changes in Vs with respect to Vp and the Vp/Vs value itself. The Vp/Vs value is often closely tied to lithology. For example, Miller and Stewart (1990) use data from full-waveform sonic logs in the Medicine River field in Alberta to analyse ratios from more pure lithologies (sandstone, shale, limestone - Figure 1). Similar to values reported by other authors, the Vp/Vs values here for sandstone cluster around 1.6, for shale and limestone near a value of 1.9. When the lithologies become more mixed or complex the Vp/Vs values change to more intermediate quantities.

Similarly, in analysing an array sonic log from the Davey well (3-13-34-29W4) in central Alberta, Miller (1992) plotted Vp/Vs values, PEF (photoelectric cross section) curves, and anhydrite and dolomite fractions. In Figure 2, we note that Vp/Vs from the array sonic tracks the PEF curve and volume of anhydrite quite well - as the anhydrite versus dolomite fraction increases so do the Vp/Vs and PEF logs. Anhydrite values are about (2.0), dolomites are about 1.85. Figure 3, shows the correlation of Vp/Vs with dolomite (1.85) and limestone (1.95). Again, as the limestone fraction versus dolomite increases so do the Vp/Vs and PEF logs. The log values are important also in generating synthetic seismograms which assist in interpreting P-P and P-S sections. An example is from the Blackfoot field in southern Alberta (Figure 4). Small sections of logs and their corresponding synthetic seismograms are plotted here.

VSP surveys

VSP surveys generally use 3-C geophones and have done so for many years. This is largely a result of P and S waves propagating off the vertical in the subsurface. So there is P-wave data in the horizontal plane and S-wave energy on the vertical channel. 3-C analysis can separate the P- and S-wave energy. Interestingly, VSP processing had an impact on P-S surface analysis: the P-wave reflectivity trajectory is a curve in the VSPCDP map and so is the P-S reflection curve in surface seismic geometry. This helped researchers understand of how to do Common Conversion Point (CCP) mapping for the P-S data in a surface geometry.

A basic use for the VSP survey is to determine seismic interval velocities. An example from the Hamburg area of central Alberta is shown in Figure 5. We note the low Vp/Vs value of the porous dolomite with respect to the surrounding limestones.

We can also assemble well logs, VSP data, synthetic seismograms, and surface seismic into a compelling display called a composite plot. This is a very useful compendium of correlated data often allowing a more confident interpretation. For example the composite plot from the Rolling Hills are of southern Alberta is shown in Figure 6. We note that in the subsurface P-P and P-S events have about the same frequency content (Geis et al., 1990, Coulombe et al., 1996). Figure 7 from the Rolling Hills area of southern Alberta gives an example of this similarity. Unfortunately however, by the time the P-S events are recorded at the surface their frequency has often decreased relative to that of the P wave (Figure 8). Geis et al. (1990) used 3-C VSP measurements to estimate seismic velocities in the subsurface as well as to correlate P-S data with its corresponding P-P data. They found that P-S waves and P-P waves were recorded with the same polarity. They also saw a clear correlation among the synthetic seismogram, VSP, and surface seismic data.

Zhang et al. (1994) also assembled a composite plot which included P-S offset VSP data. In Figure 9, we can see the correlations with P-S surface seismic data as well as the P-S VSP section. The in situ data is much higher resolution than the surface data. Another example of P-P and P-S VSP data comes from the Willesden Green region of central Alberta (Figure 10). On the P-S section we see much more reflection activity in the shallow section as compared to the P-P section (Stewart et al., 1993).

Coulombe et al. (1996) considered AVO effects in the VSP in the carbonate section (Figure 11). They found that P-S and P-P AVO effects were in evidence and could be modeled (Figures 12 and 13). In the VSP data the P-S section gave a higher resolution picture in which the top and bottom of the porous zone could be identified.

In another case of P-S imaging at the Judy Creek area (Campbell et al., 1994), both P-P and P-S images helped identify a porosity development that the well had missed (Figure 14).

3-C Surface Seismic Acquisition

One of the earlier discussions on the surveying, analysis, and interpretation of converted waves was published by Garotta et al. (1985). They used a two-element geophone for acquisition. The data recorded were quite good. Although now we would generally recommended using a three-component geophone so that off-line effects, mis-orientation, anisotropy, crooked lines, and 3-D shooting can be handled.

Lawton and Bertram (1993) tested four 3-C geophones, using a source at various azimuths to the receivers. They found that all of the geophones tested performed well except one which is now off the market. This was important to further establish the fidelity of the field measurements before proceeding on to sophisticated processing. Eaton and Lawton (1992) analysed the fold of P-S sections and found it to be highly oscillatory under certain conditions - when the source line interval is an even integer of the receiver spacing. They recommended odd-spacing configurations or additional processes such as adjacent trace averaging or DMO.

Lawton et al. (1995) discuss the design of 3C-3D surveys. They show the importance of using source line and receiver spacings that are not even multiples of each other. One must carefully consider converted wave design so as to not have lines or regions of low fold.

Comparing data from a 9-C survey in Olds, Alberta (Yang and Stewart, 1996), we find excellent P-P data, very good P-S data, good S-S data. The other sections were quite noisy. The tie between the various sections is quite compelling and can be used to develop Vp/Vs values. These are discussed later.

Three-component geophones have sometimes been in short supply. Because of the current necessity of orienting the geophones carefully, many of them are laid out prior to recording and not moved. There are still issues about the use of arrays or single phones. Generally, buried geophones provide a better signal with less noise. It would also be useful to have a geophone which could automatically level or orient itself.

Gimbaled devices are used in VSP surveys as well as marine cables. Auto-orienting surface geophones are under development. The increase in available recording channels and 3-C geophones over the past several years has made the 3-C survey more feasible. Other issues for P-S data acquisition include source type for optimal generation of converted waves and special recording cables with three channel take-outs and simple connectors. There is always a need to have less expensive acquisition. This is arriving as more experience in 3-C acquisition is gained.

P-S data processing

Several authors presented analysis of the asymmetric reflection point trajectory (Chung and Corrigan, 1985; Tessmer and Behle, 1988) and its importance in P-S imaging. Garotta (1985) outlined procedures for handling P-S data and presented additional interpretive uses for the data. Stewart (1991) extended Chung and Corrigan's (1985) work to describe converted waves where the source and receiver had unequal elevations. This and other work on binning led to the creation of further P-S sections.

Garotta et al. (1985), as mentioned previously, published one of the earliest papers on the interpretation of P-S data. This insightful paper processed P-P and P-S data by analysing vertical and horizontal channels separately with different statics and velocities. Also, the concept of what was later called, "asymptotic binning" was introduced and they produced their final P-S sections using this gather and binning method.

Also because of the low S velocity in the near surface, receiver statics in the P-S survey can be large. Lawton (1990) gave numbers of about 70 ms for the receiver static. Cary and Eaton (1993) found receiver statics of 100 ms. Isaac (1996) showed receiver statics of 100 ms. in a case from Cold Lake, Alberta. They also derived a new method of calculating these statics using trace-to-trace coherence. The near surface has a marked influence on the P-S data by large and variable statics. But, the near surface has another undesirable effect: attenuation. This remains a limitation of surface P-S analysis. Perhaps further work on statics resolution Q filtering, and imaging will help.

Separation of P and S events on the full 3-C record has been approached using various techniques. In VSP analysis, methods based on Dankbaar's (1985) scheme have proven useful. Other work using 3-C arrays to reduce noise as well as estimate direction and wave type looks promising. In carrying the analysis of P-S waves further, Slotboom (1990) considered the velocity analysis problem. He derived a shifted hyperbola equation for NMO correction that can correct the offset traveltimes better than a normal hyperbolic velocity analysis. After NMO, it is important to understand the Fresnel zone (or the averaging aperture in a stacked section) and the potential of P-S data to be migrated. Eaton et al. (1991) derived the P-S Fresnel zone and found that for the same frequencies, the P-S Fresnel radius is smaller than the corresponding P-P case. However, with the lower P-S frequencies often observed at the surface P-P and P-S radii work out to be about the same. They also showed that P-S data could be migrated post-stack in a kinematic sense. Harrison and Stewart (1993) considered the migration problem further and derived a P-S migration velocity for a layered material. Harrison (1992) also developed an equation and procedure for DMO correction of converted wave data. Stewart (1991) derived a method for converting S-wave reflectivity to a shear-velocity log. This method is similar to the seismic inversion via the Seislog method. Stewart and Ferguson (1996) also presented a method to find a Dix S-wave interval velocity from P-S stacking velocity. Cary (1994) details the processing flow for P-S waves in a 3-D survey. There is considerably more room in P-S analysis for enhancement of the data. Receiver static remain a large problem as does adequate NMO-correction, and P-S imaging. The effects of anisotropy and multi-mode conversions degrade the sections.

Interpretation techniques

Lawton and Howell (1992) developed a P-S (and P-P) synthetic seismogram program to assist in the correlation and interpretation process. This modeling algorithm uses the offset dependent reflectivity and ray-traced traveltimes of both P-P and P-S waves to create synthetic seismograms.

Finally, Larson and Stewart (1994) have developed interpretation techniques for the analysis of P-S data in 3-D geometry. From one 3C-3D seismic survey come three products: the P-P volume and the anisotropic (P-S1 and P-S2) volumes. We can now develop 3-D Vp/Vs values as well as have two independent sections to compare, contrast, and integrate. The frequently lower S/N ratio in 2-D converted wave sections may be made significantly better by 3-D surveys.

CASE HISTORIES

Lithology detection

Garotta et al. (1985) show P-S and P-P data for the Viking sand channel reservoir in the Winfield, Alberta oil field. They found amplitude anomalies on the P-S data correlating with the known boundaries of the reservoir. They also used isochron ratios to determine Vp/Vs. They found low Poisson's ratios indicating sand off the neighbouring shales. using Poisson's ratio (derived from tp/ts interval times) and defining a sand/shale lateral variation to delineate an oil-saturated Viking sandstone reservoir (Figure 15).

Nazar and Lawton (1993) used AVO stacks, P-P, and P-S sections to analyse the productive regions of the Carrot creek field (Figure 16). The oil-saturated conglomerate in this region is not well imaged by conventional data but is readily apparent on P-S sections.

Vp/Vs is significant in another carbonate play region in Lousana, Alberta (Figure 17). Miller et al. (1996) found variable Vp/Vs values in this region. The Vp/Vs values in the Cretaceous section (2.2-2.5) are indicative of a clastic section while those in the Paleozoic (1.5-2.0) are characteristic of carbonate rocks. The lower values in the Paleozoic, from shot point 172 to 212, are coincident with an underlying oil-bearing reef. The reef may have had some effect on the subsequent deposition leading to a seismically visible anomaly.

Yang and Stewart (1996) reviewed a 9-C seismic survey from the Olds, Alberta area. This 10.3 km survey used vertical and horizontal vibrators as sources along with 3-C geophones. The P-P section was of very good quality, followed by the P-SV section and then the SH-SH section (Figure 18). The other components were fair to poor. They noted that there were Vp/Vs anomalies over a producing gas field going from non-producing to producing facies (Figure 19).

The Blackfoot seismic experiments were conducted to identify sand reservoir facies from non-reservoir rocks. A series of surveys including broad-band 3C-2D data, full 3C-3D data, 2-D and 3-D VSP surveys were conducted (Figure 20). The p[processed P-P and P-S sections tie reasonably well (Figure 21). We find a nice correlation with P-S amplitude and Vp/Vs anomalies over known oil production (Figure 22). When we look in more detail at the 3-D data we find some fascinating and compelling anomalies. First when viewing the P-P data time slices (e.g. Figure 22), we see some anomalies over the reservoir but also off-production false positives. P-P isochrons are also indicative of the channel but not without some ambiguity. The P-S amplitude seems to give a more definitive (but lower resolution) image of the sand channel (Figure 23). P-S isochrons are even more cogent (Figure 24). The Vp/Vs maps are another strong indicator of sands and reservoir (Figure 25).

Poor P-wave areas

P-wave energy can be scattered and attenuated when passing through gas-saturated strata. Leaky gas reservoirs can release a halo of gas which makes conventional; imaging and characterization of the reservoir very difficult (Figure 26). S waves on the other hand are generally less sensitive to rock saturants and can be used to penetrate gas-saturated sediments. The SUMIC (sub-sea seismic) technique uses 3-C geophones planted on the ocean bottom (Berg et al., 1994). S-wave data can be recorded with these ocean-bottom geophones. From these recordings, P-S images can be made using the previously described techniques. A remarkable example of this imaging through a gas chimney is shown in Figure 27 (Granli et al., 1995).

In cases where there are volcanic (e.g., basalts), carbonates, salts, or even permafrost in the near surface, seismic imaging may be complicated or compromised. Purnell (1992) uses a physical model with a single high-velocity layer to demonstrate some of the modes that are observed in such a case. P waves convert to S waves with high efficiency going from low to high velocity layers. He finds that when migration is targeted to use these events (SPPS, SPPP, PPPS) some significantly improved images can be obtained. Poley et al. (1989) found that multi-mode conversions were important for shallow imaging in the Canadian Beaufort Sea.

Reservoir monitoring

Isaac (1996) reports changes in the reservoir character when analysing Vp/Vs anomalies associated with steam flooding in as heavy oil reservoir at Cold Lake, Alberta (Figures 28, 29). She found that Vp/Vs could discriminate between hot, warm, and cold parts of the reservoir (Figure 30).

Gas detection

Garotta et al. (1985) give a case of identifying a gas anomaly from a Miocene basin in a sand/shale environment. They determined a Poisson’s ratio from P-P and P-S sections and overlaid that on the P-wave section. A low Poisson’s ratio is the site of a productive gas well. About 2 km to the left of this feature is a P-wave anomaly without a corresponding Poisson ratio decrease. A well drilled here was dry.

Structural imaging

High-angle features can be more resolvable using converted waves in certain circumstances. Purnell (1992) shows examples from physical modeling data where high angle anomalies were more visible on migrated P-S data than migrated P-P data. High-velocity near surfaces also have the potential to allow both P and S energy to propagate at angles away from the vertical. This puts the P-P and P-S energy on both vertical and radial channels.

Anisotropy and fracture analysis

Stewart et al. (1995) interpreted crossed P-S lines and VSP data from the Willesden Green area of Alberta. The survey was designed to find anisotropy in the Second White Speckled shale. The data recorded were excellent and the tie between VSP and surface seismic was very good (Figure 31). However, there was no obvious anisotropy.

Ata et al. (1994) find evidence of azimuthal anisotropy interpreted to be associated with fracturing in 3-C data from southwestern Venezuela. Numerical modeling (Li et al., 1996) suggests that gas-saturated oriented fractures may have a distinct effect on P-S velocity (Figure 32).

WHAT'S LEFT TO DO

Investigating other modes in 3-C data will allow us to separate undesirable modes from wanted ones as well as make other sections. In some cases, a vertical vibrator may also generate enough S-wave to allow an S-S section to be created directly. Fyfe et al. (1993) show a case from Saudi Arabia in which good P-S and S-S sections were produced from a vertical vibrator source recorded into 3-C geophones. Furthermore, an S-S section may be produced from dynamite data Nieuwland et al. (1994) give an example of processing a P-S-S survey in the Netherlands. In this case, an upgoing P wave from the dynamite source converts at the surface to a downgoing S wave that is reflected back to the surface from various layers as an S-wave. Credible S-wave sections are produced, along with their P-wave counterparts, and are interpreted for gas effects. Sometimes these multi-modes are less desirable.

More sophisticated processing techniques will be useful to estimate statics, identify and use anisotropy, estimate velocities, and do accurate migrations. We also need to understand a great deal more about how the near surface damages S-wave data.

There are many areas of poor data recording such as the Michigan Basin and Rocky Mountain Foothills. We are challenged to understand why these areas are no-record (NR) and what we can do about that. P-S imaging in very structural environments may produce credible images

CONCLUSIONS

The reflection seismic method has used P waves for many years - and with great success. However there is more to be done with exploration seismology: For we always need better resolution in our final sections, higher signal-to-noise ratios, new stratigraphic and structural images, and images that directly give petrophysical information. There's lots left to do with seismic, especially converted waves.

P-S analysis has been developing for about 10 years. There are many more papers now being published. In research terms, we know a great deal about P-P waves and how to extract useful information from them. Much less has been done with P-S waves. The current results indicate that there is lots of useful information in them too

A recent session on multicomponent exploration at the 1996 EAGE in Amsterdam and an upcoming special session at the SEG in Denver show an increasing interest in the method and its usefulness.

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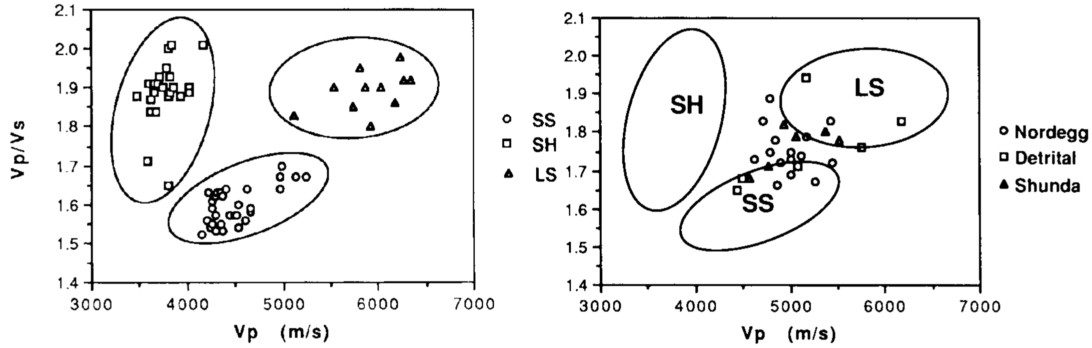

FIG. 1. Well log Vp/Vs values versus Vp for pure and mixed lithologies of the Medicine River field (from Miller and Stewart, 1990)

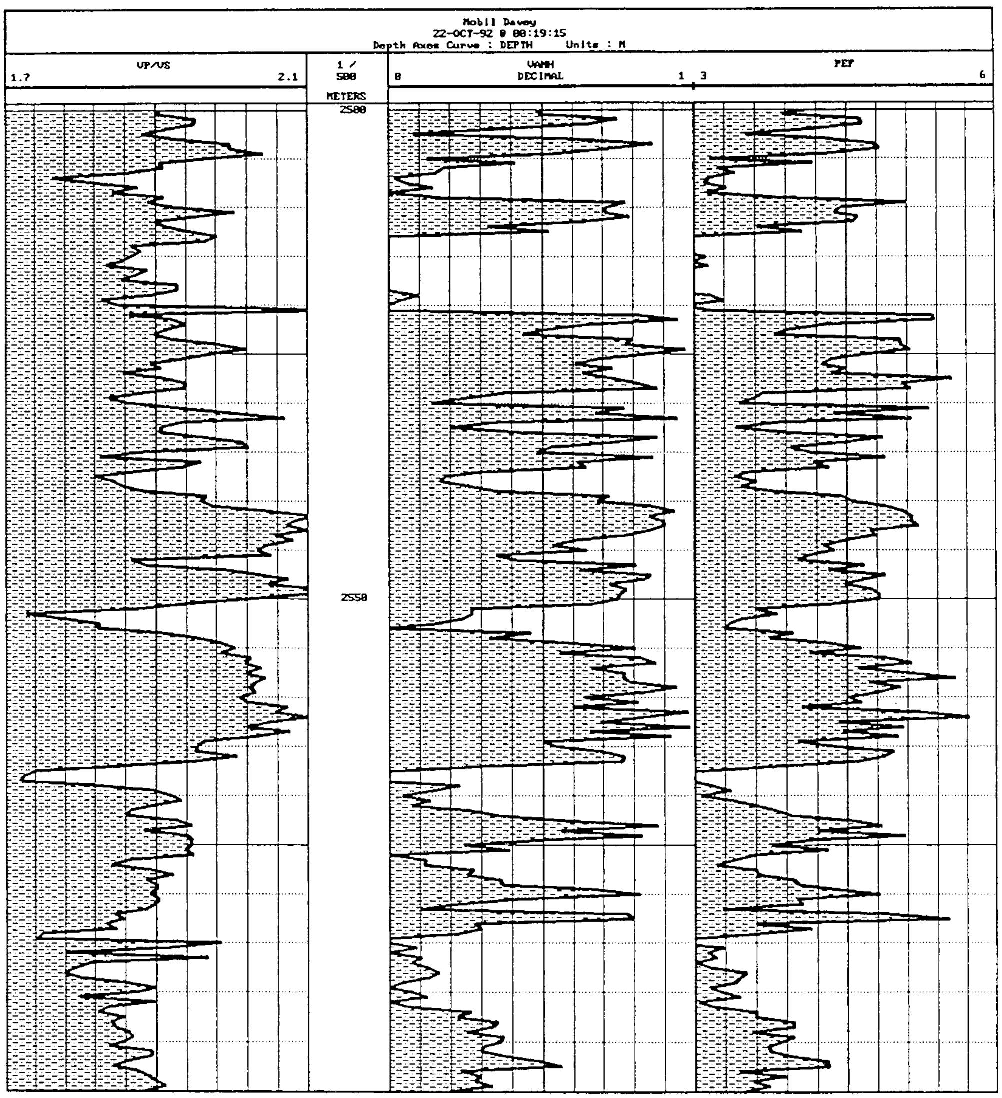

FIG. 2. Vp/Vs, volume anhydrite, and photoelectric logs plotted in depth for the Davey well. Note the consistent tracking of Vp/Vs with the anhydrite volume (from Miller, 1992).

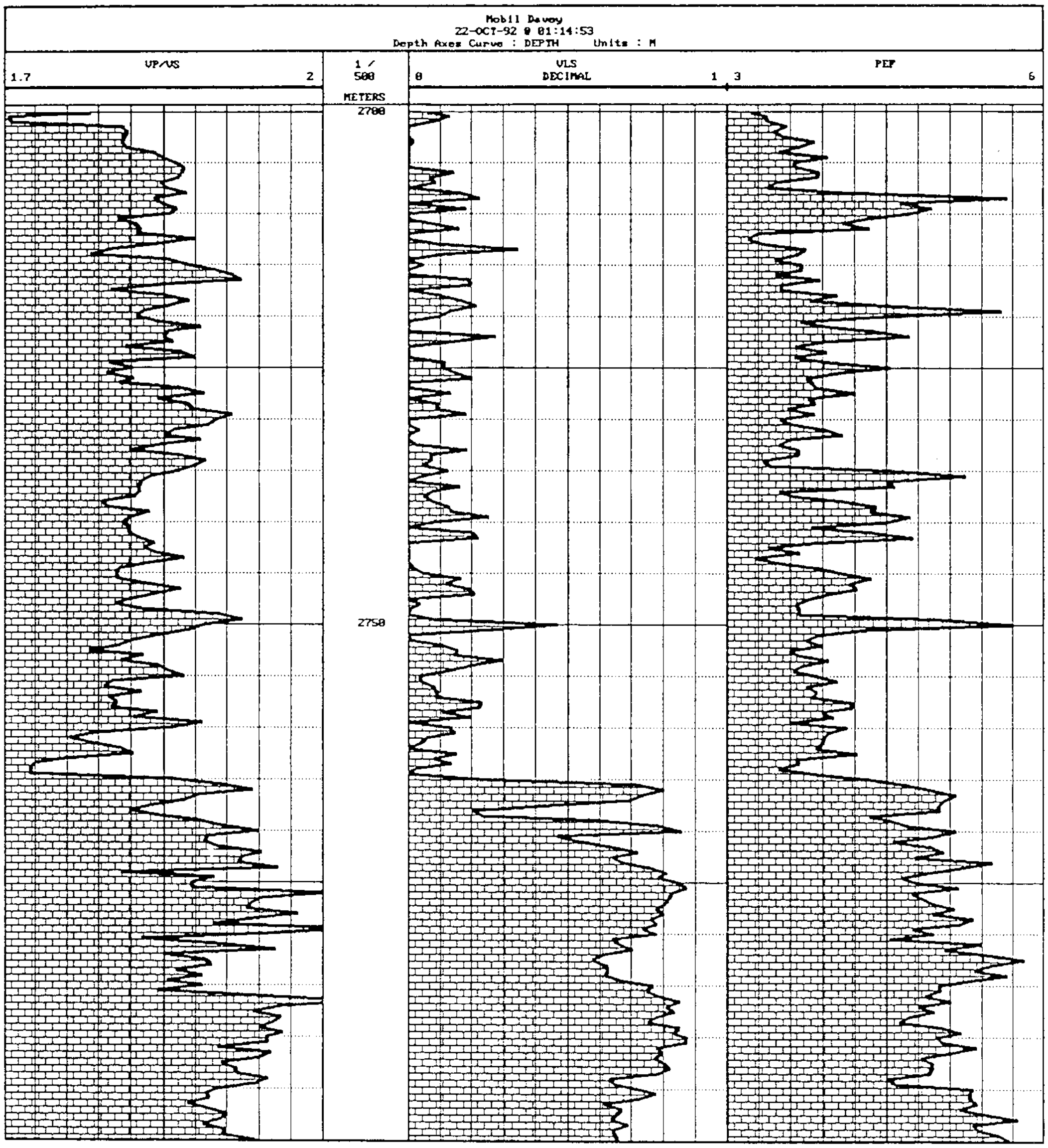

FIG. 3. Vp/Vs, volume limestone, and photoelectric logs plotted in depth for the Davey well. Note the consistent tracking of Vp/Vs with the limestone volume (from Miller, 1992).

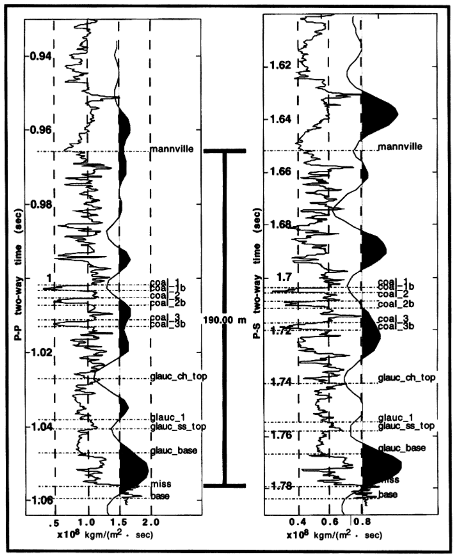

FIG. 4. P-wave log and P-P synthetic seismogram and S-wave log and corresponding P-S synthetic seismogram for the 08-08-23-23W4 well in the Blackfoot field, southern Alberta (from Stewart et al., 1996)

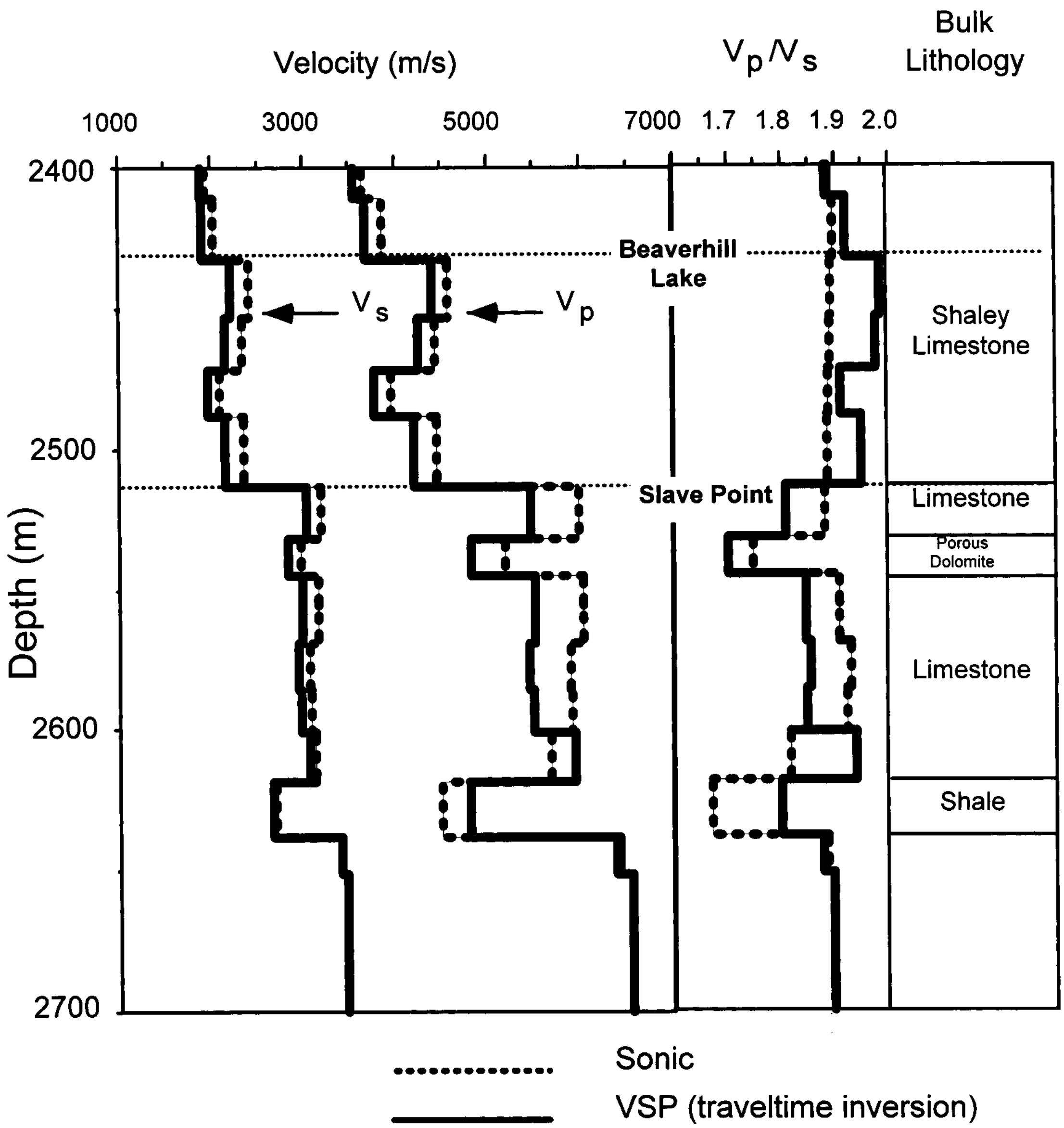

FIG. 5. Interval velocity from VSP and blocked logs. The porous dolomite reservoir shows a significant Vp/Vs drop relative to surrounding limestones (from Coulombe et al., 1996).

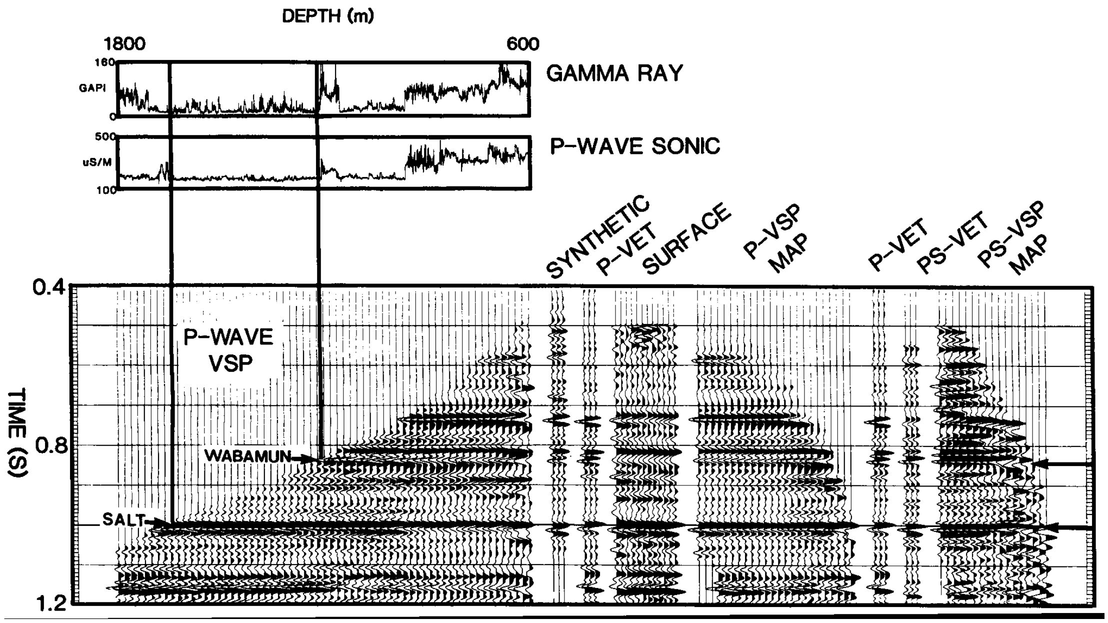

FIG. 6. Composite plot showing well logs in depth, the VSP in depth and two-way traveltime, synthetic seismograms, P-wave surface seismic, and VSP sections. Data are from S. Alberta. Note the great reflection activity (and noise) in the converted-wave section (from Geis et al., 1990).

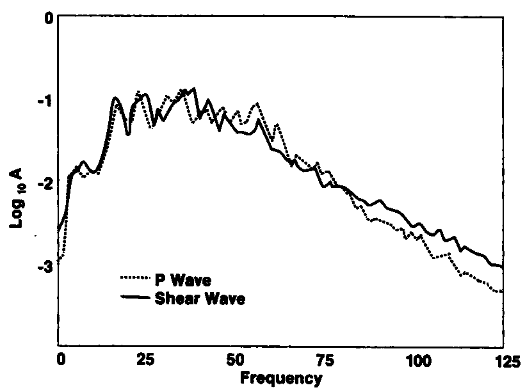

FIG. 7. Spectra from the P-wave VSP and P-S VSP data. The same temporal frequency of P-wave and S-wave data indicates a higher spatial resolution of the S-wave data (from Geis et al., 1990).

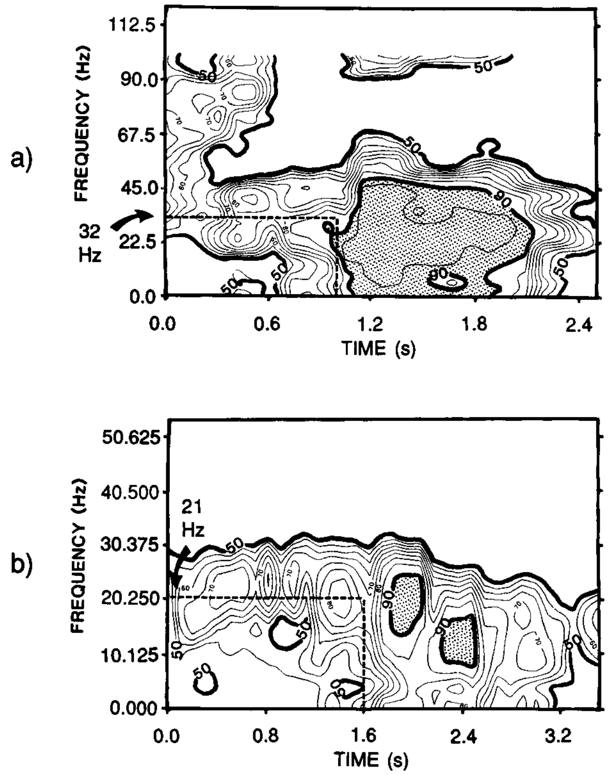

FIG. 8. Frequency coherency spectra from the Carrot Creek, Alberta surveys (a) P-P data and (b) P-S data. At the depth of interest, the P-P doiminant frequency is 32 Hz and the P-S value is 21 Hz (from Eaton et al., 1991).

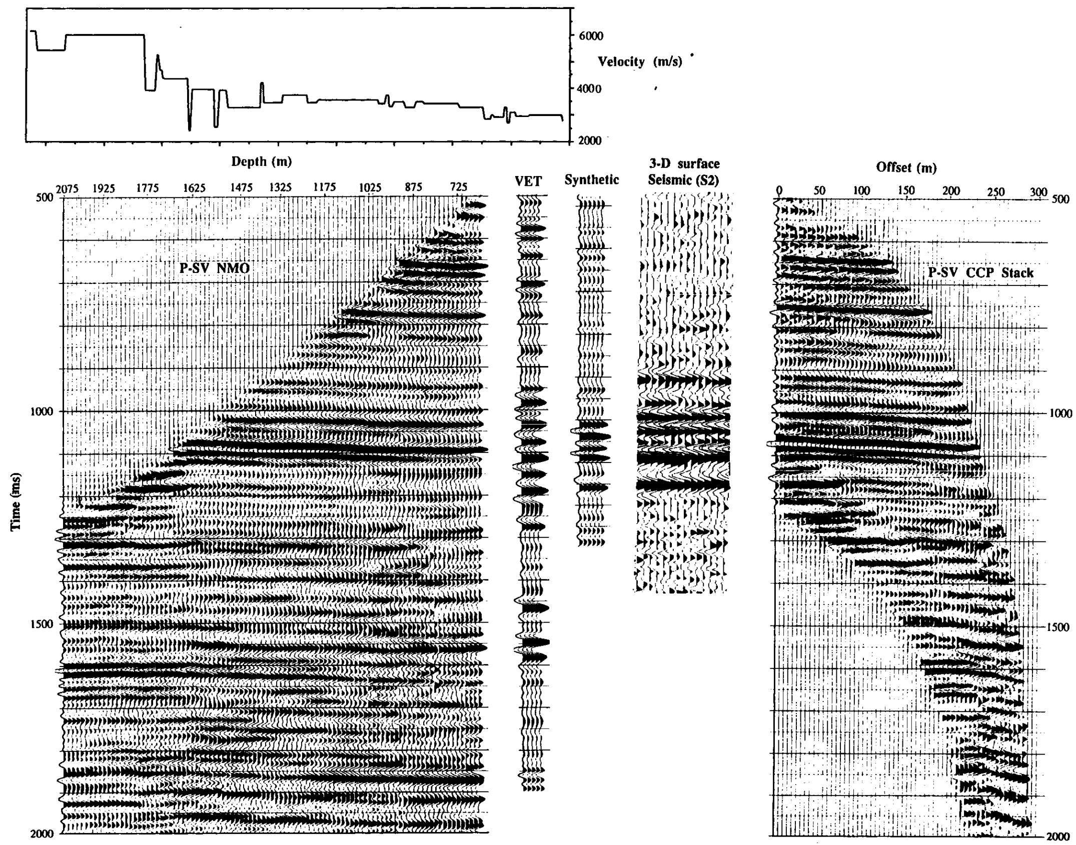

FIG. 9. Composite plot showing the velocity in depth, the VSP in depth and two-way traveltime, synthetic seismograms, P-S surface seismic, and P-S VSP section. Data are from Joffre, Alberta. Note the much higher frequency content of the VSP data (from Zhang et al., 1994).

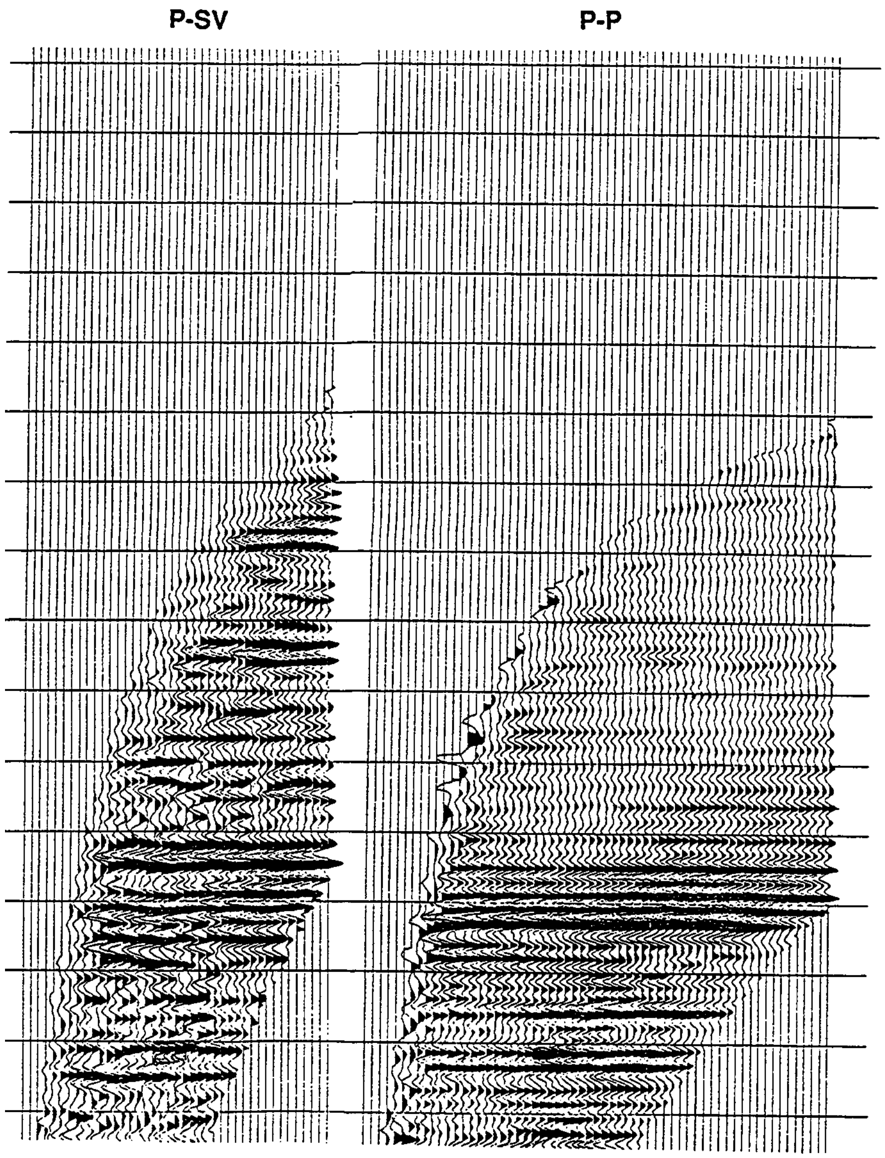

FIG.10. P- and P-P VSP sections from the Willesden Green surveys (Stewart et al., 1993). Note the greater reflection activity in the P-S section in the shallow regions.

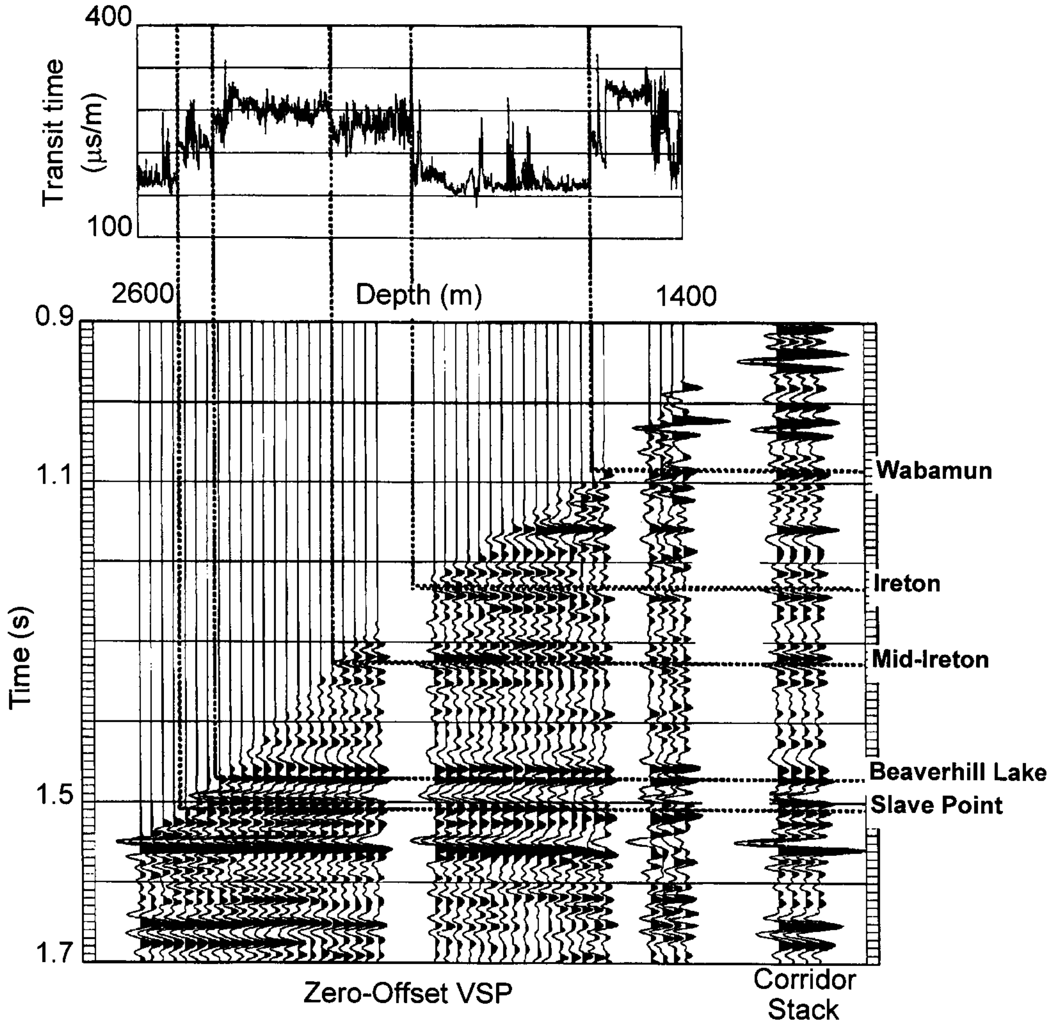

FIG. 11. Composite plot showing sonic log in depth, the VSP in depth and two-way traveltime, and VSP corridor stack. Data are from the Hamburg, Alberta (from Coulombe et al., 1996).

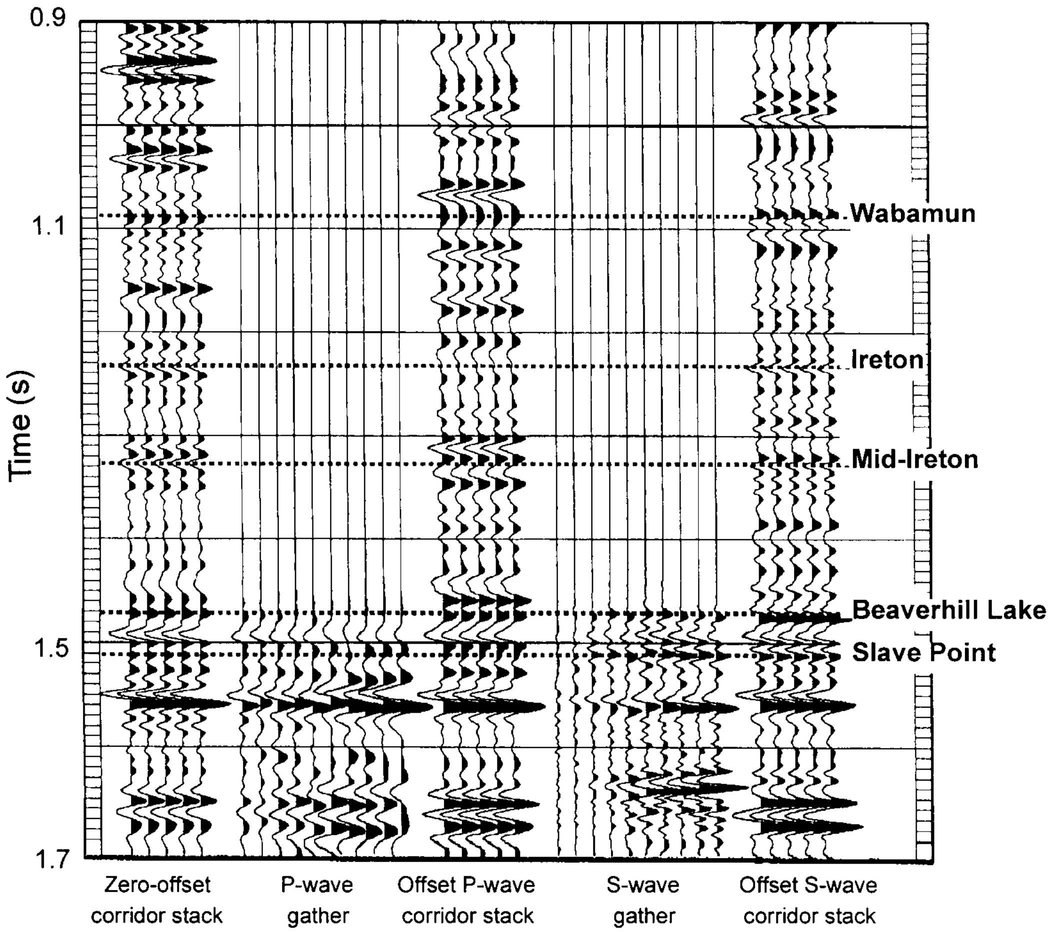

FIG. 12. Amplitude versus offset traces for VSP data. The P-wave and S-wave gathers are from offsets ranging from 80m to 2500m (from Coulombe et al., 1996).

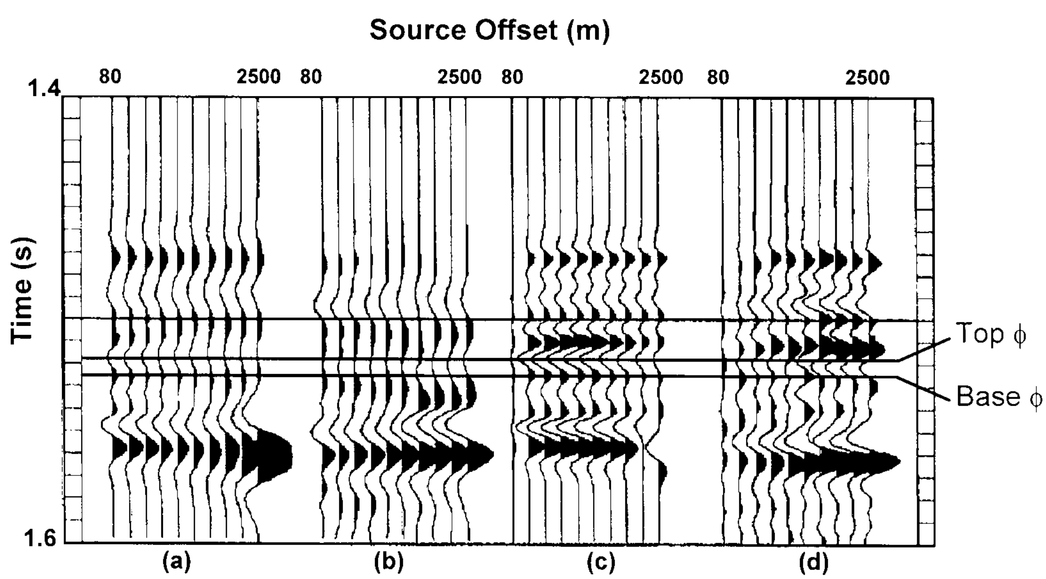

FIG. 13. Amplitude versus offset traces for VSP data. The P-wave modeled synthetic (a) and field data (b) show AVO effects as do the P-S data - synthetic (c) and field (d). The gathers are from offsets ranging from 200m to 2500m (from Coulombe et al., 1996)

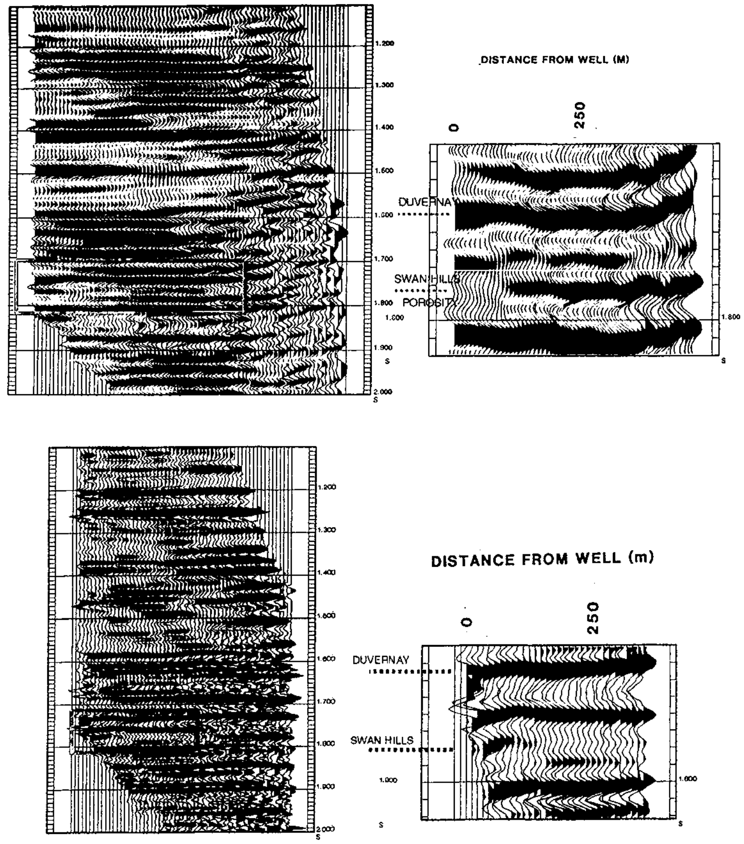

FIG.14. P-wave and P-S images from the Judy Creek, Alberta VSP surveys. Both images indicated a porosity anomaly 125 m from the well location (from Campbell et al., 1994).

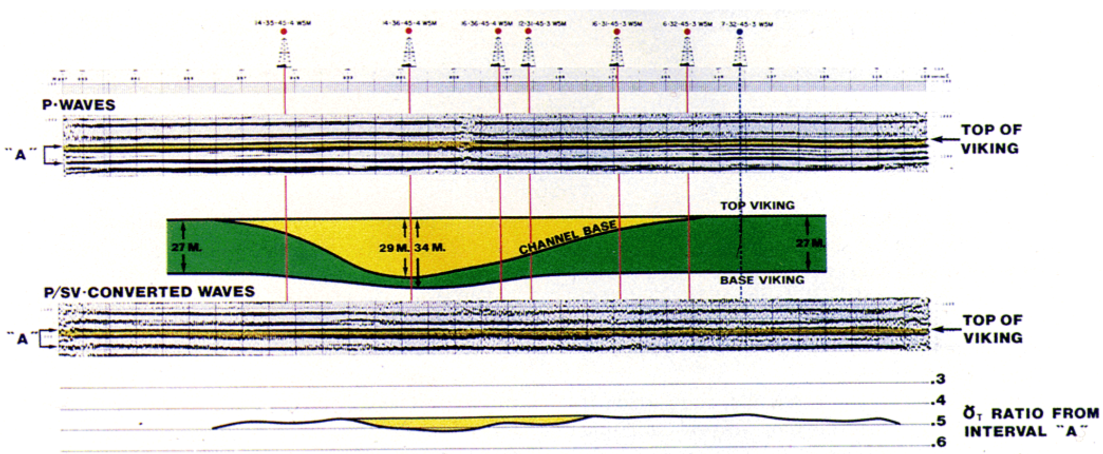

FIG. 15. Vp/Vs (gamma T) anomaly over a Viking sand channel from P-P and P-S isochron ratios (Garotta et al., 1985)

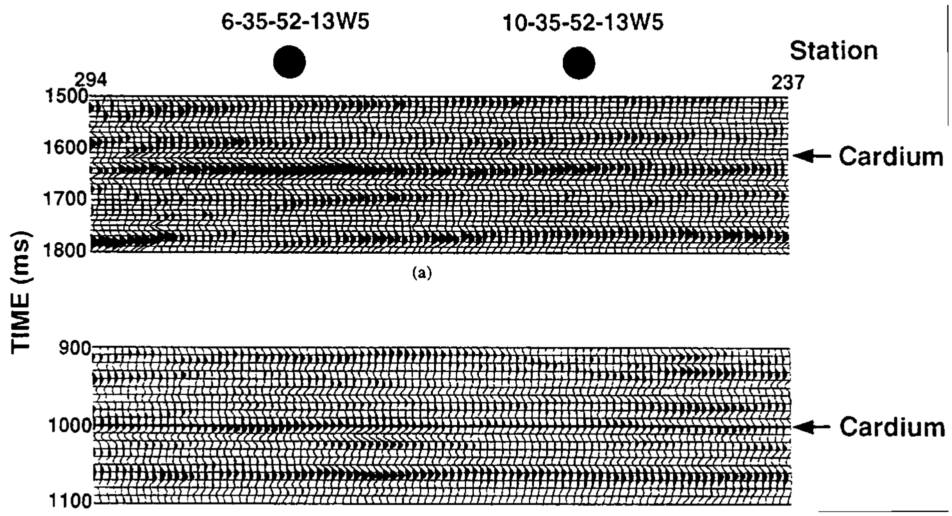

FIG. 16. Detail of the P-S (top) and P-P (bottom) sections from Carrot creek, Alberta. Note the amplitude anomaly on the P-S section at the Cardium conglomerate level (from Nazar and Lawton, 1993).

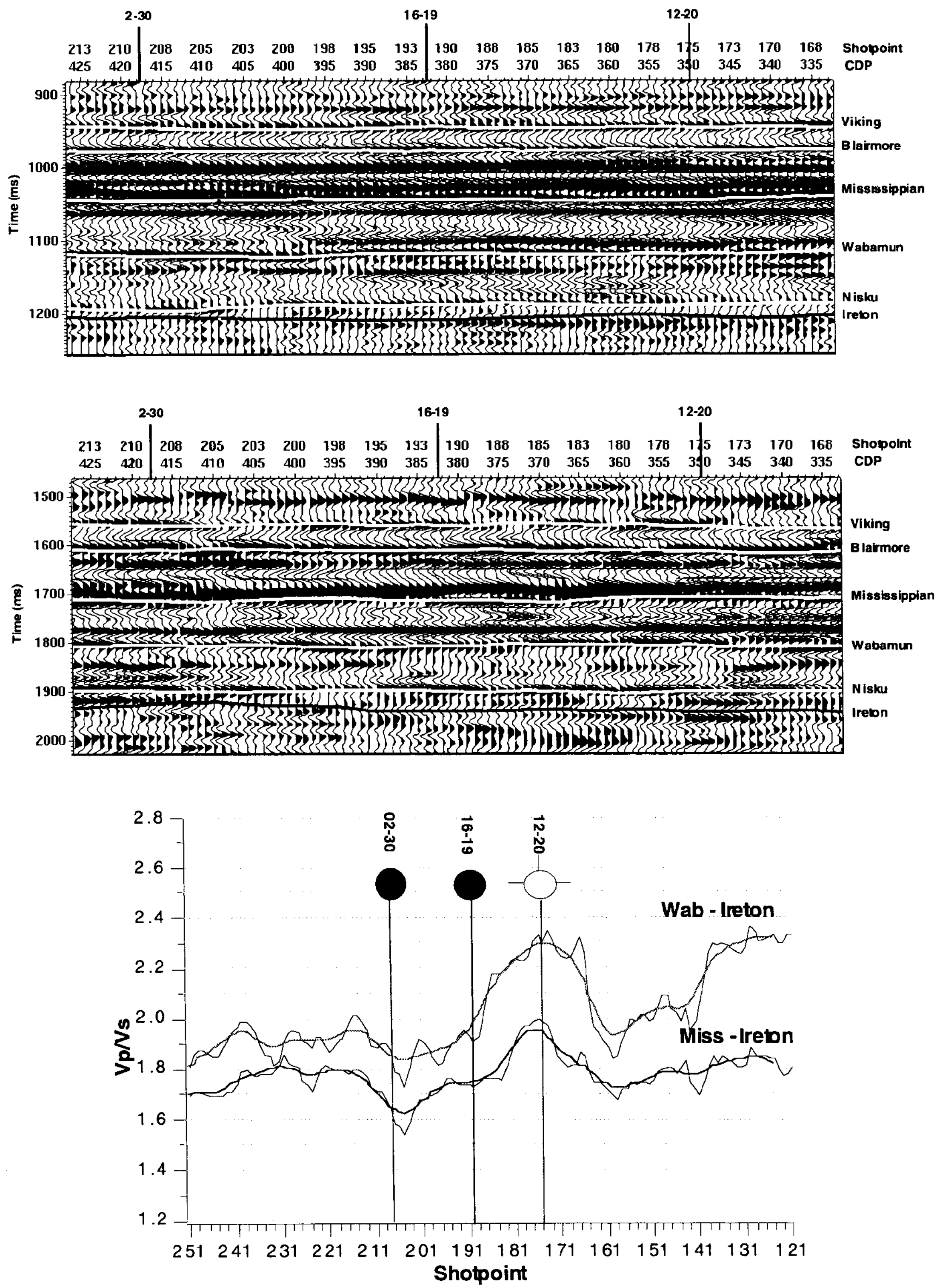

FIG. 17. P-P section (top) and P-S section (middle) from the Lousana field, Alberta. The Vp/Vs value (bottom) is extracted from the interpreted P-P and P-S sections. The lower values in the Paleozoic, from shot point 172 to 212, are coincident with an underlying oil-bearing reef (Miller et al., 1996).

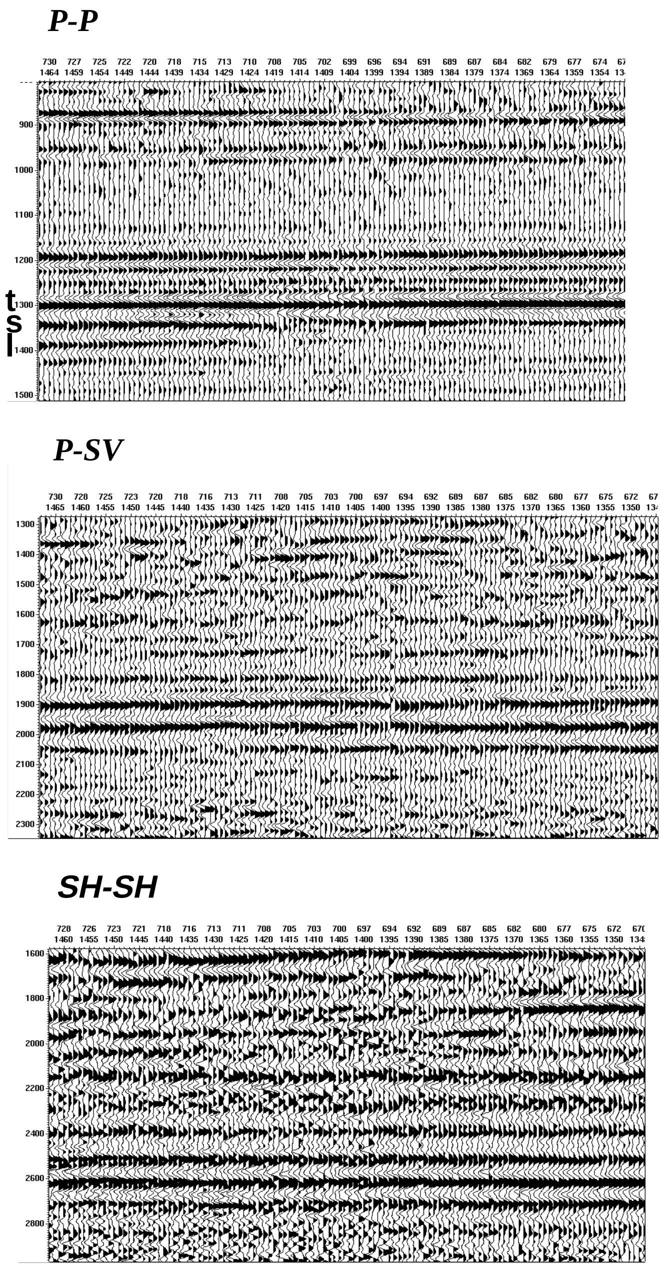

FIG. 18. P-P, P-SV, and SH-SH data from a 9-C survey at Olds, Alberta. The P-wave data are of very good qualty, the P-SV section is somewhat less noisy than the SH-SH section (from Yang and Stewart, 1996).

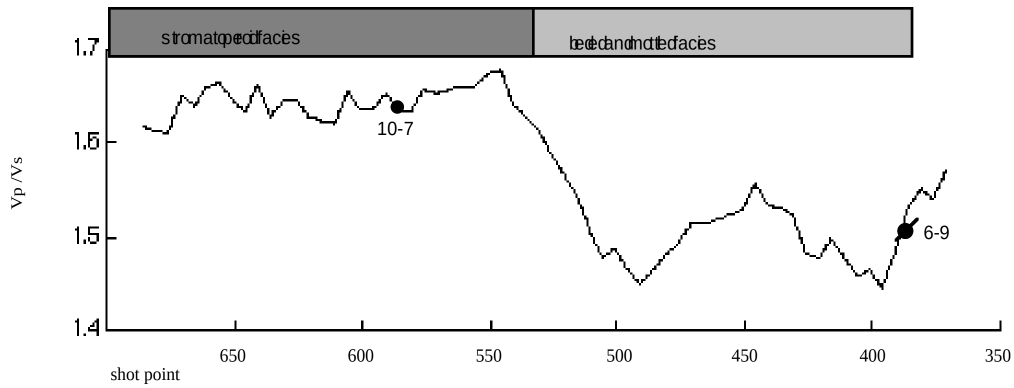

FIG. 19. Vp/Vs values from the Olds sections are coincident with productive parts of the gas-saturated reservoir.

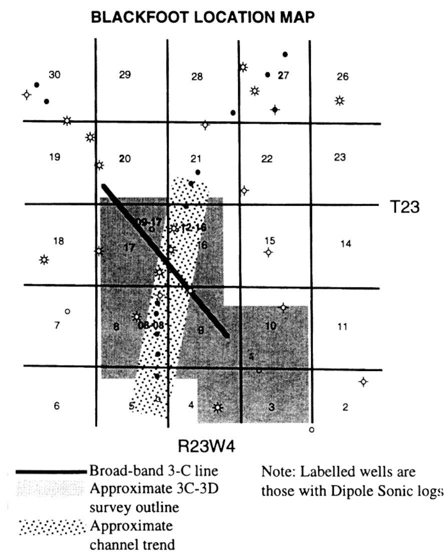

FIG. 20. Location map for the Blackfoot seismic experiments.

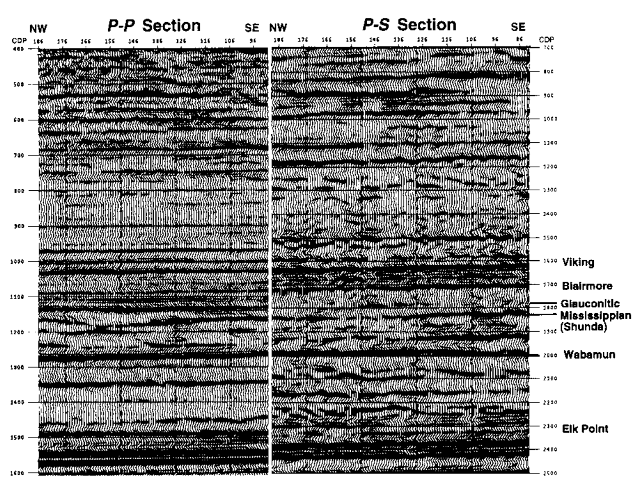

FIG.21. Correlation of the broad-band 2-D lines (P-P and P-S) over the Blackfoot field.

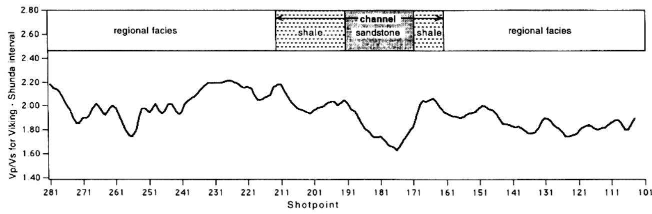

FIG. 22. Vp/Vs plot derived from P-P and P-S isopchron ratios from the top of the Glauconite channel to the Wabamun level. Low Vp/Vs values indicative of sand are shown in the light parts of the gray scale.

P-P isochron: Miss-Mannville

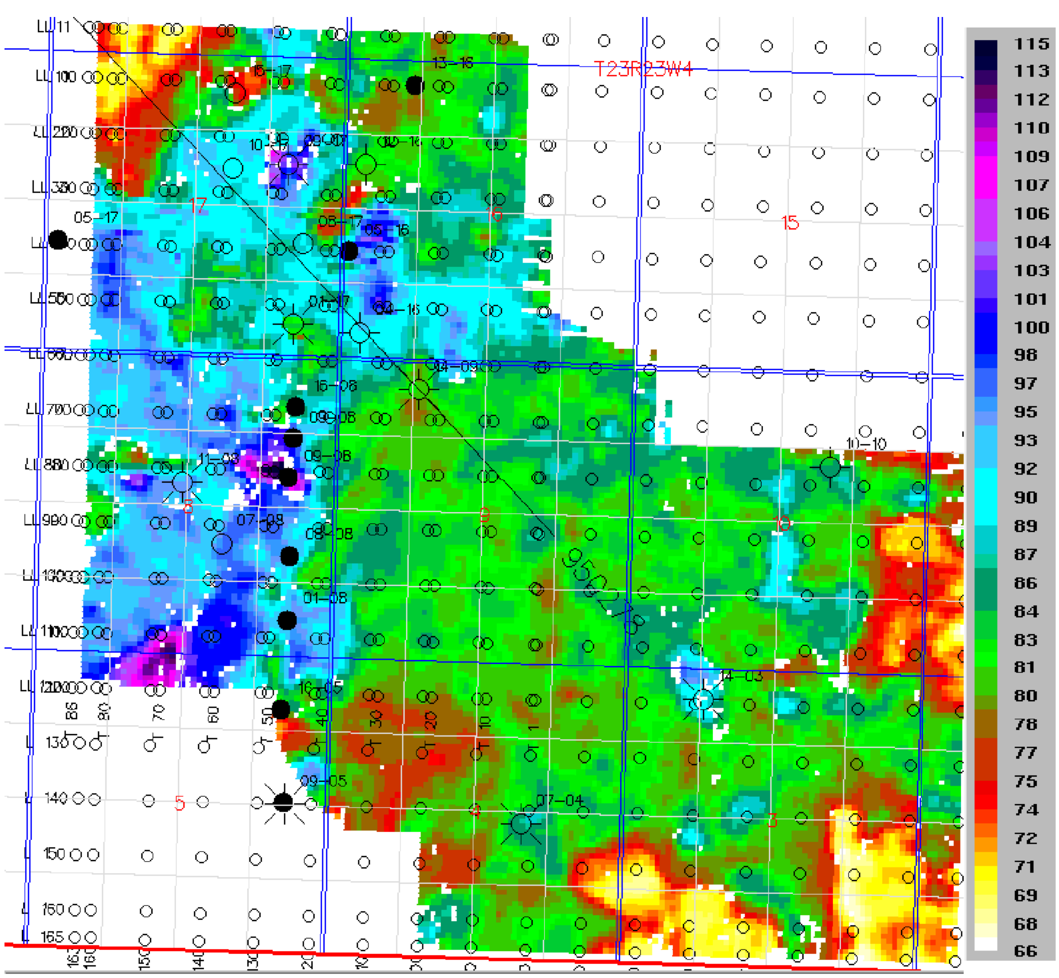

FIG. 23. P-P isochron from the Mannville to Mississippian.

P-S isochron: Miss-Mannville

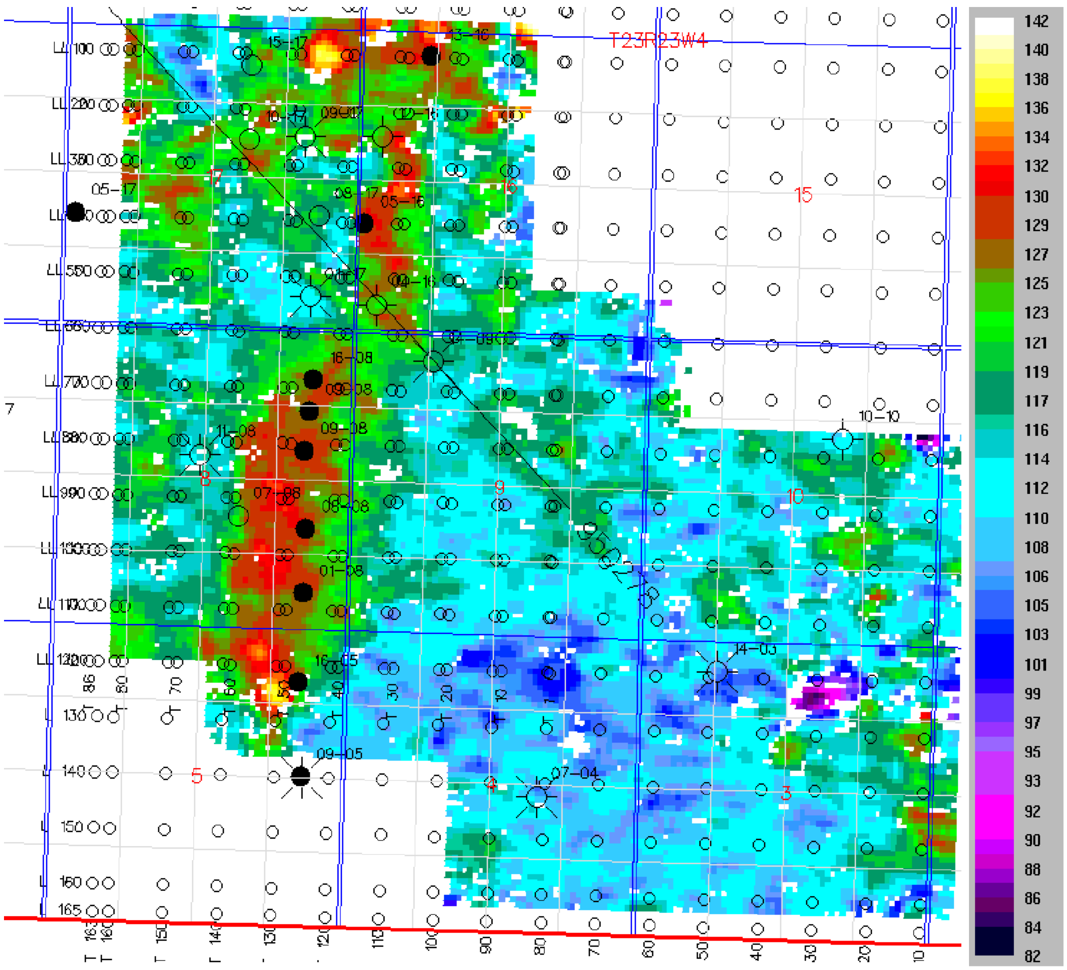

FIG. 24. P-S isochron from the Mannville to Mississippian.

Vp/Vs: Wabamun-Top channel

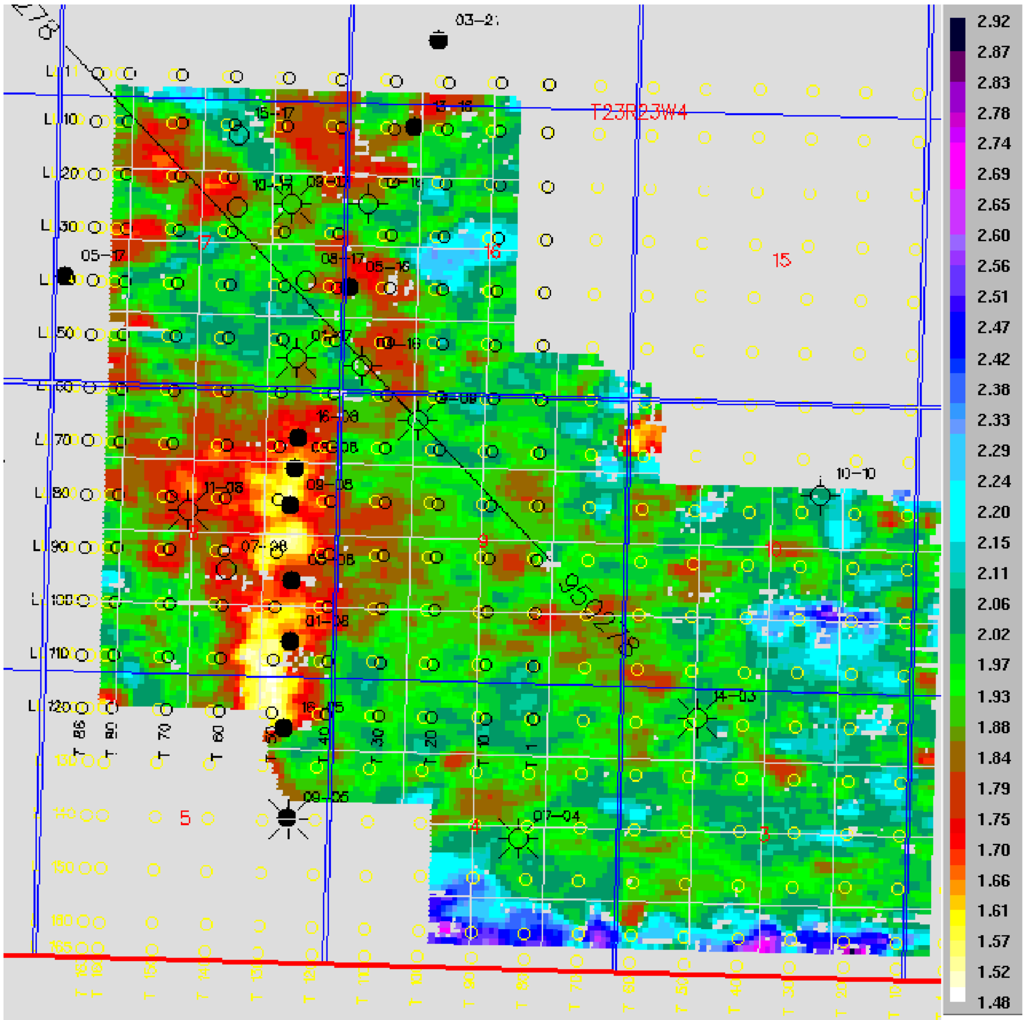

FIG. 25. Vp/Vs value map for the reservoir region (Top channel-Wabamun).

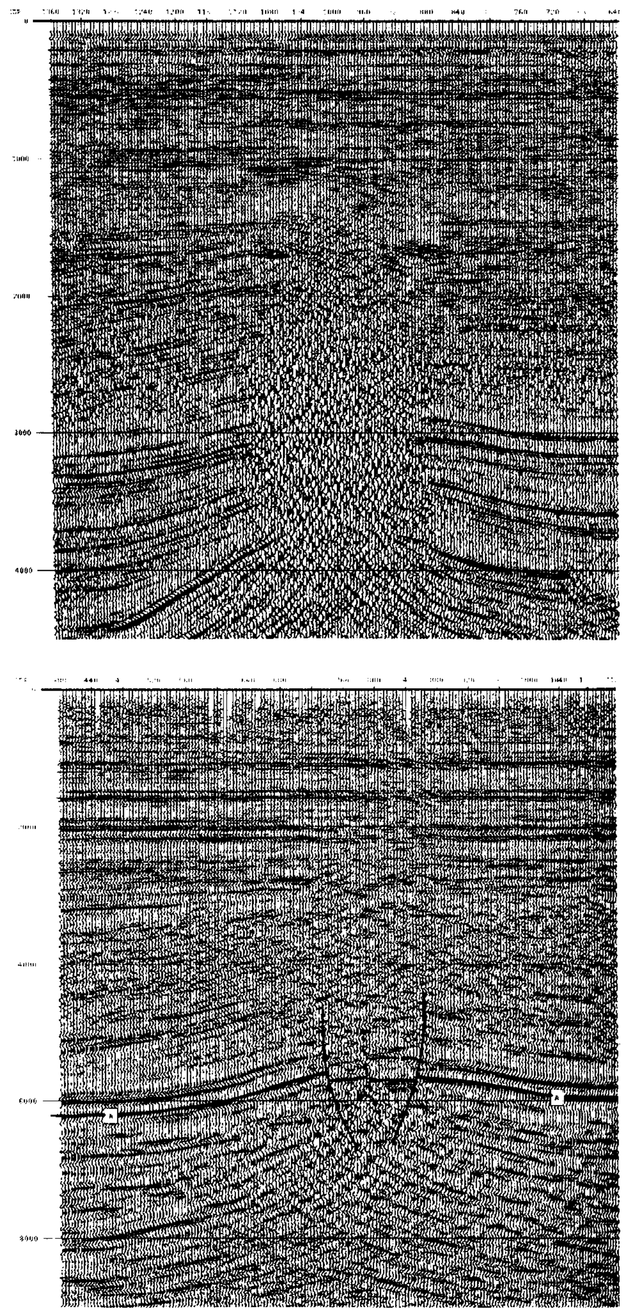

FIG. 26. P-wave data from the North Sea using as streamer (top) and a SUMIC S-wave section (bottom) from Berg et al. (1994).

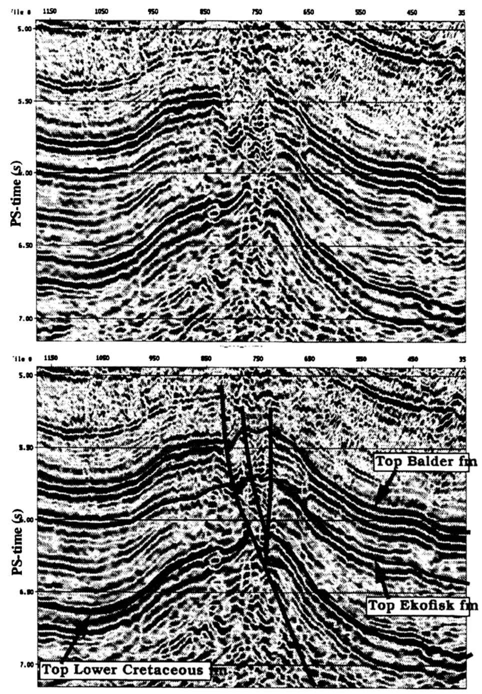

FIG. 27. SUMIC P-S wave sections with and without interpretation (Granli et al., 1995).

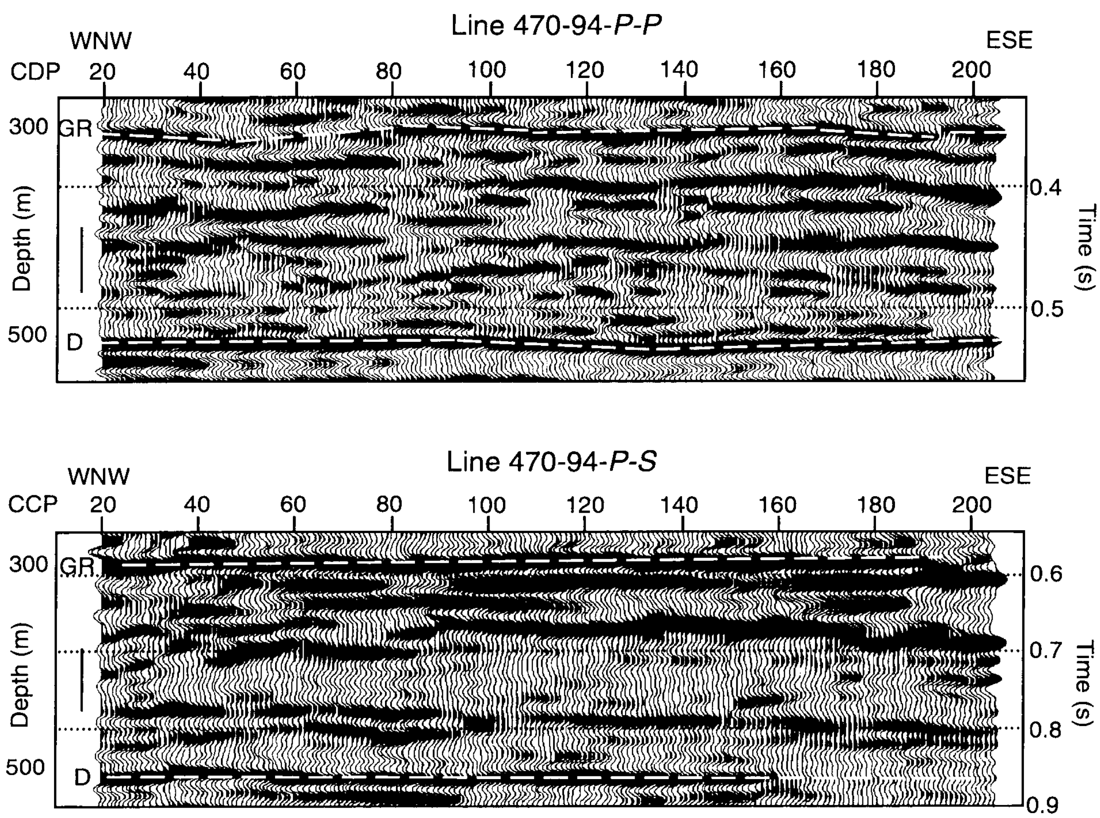

FIG. 28. P-P and P-S seismic lines from Cold Lake, Alberta. Time picks on the Grand Rapids formation (GR) and top of the Devonian are indicated (from Isaac, 1996).

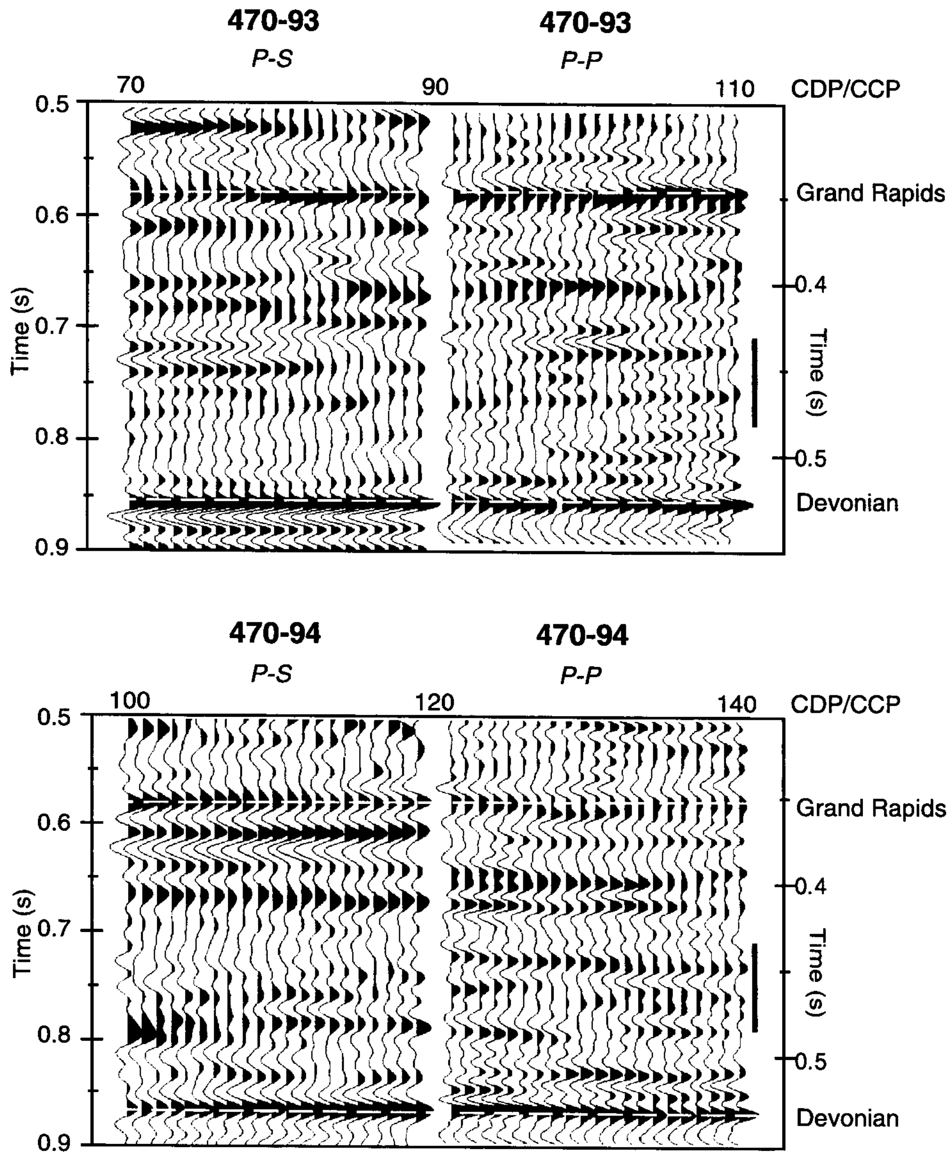

FIG. 29.Comparison of the 1993 and 1994 seismic lines. Note the similar data quality and resolution among all lines (from Isaac, 1996).

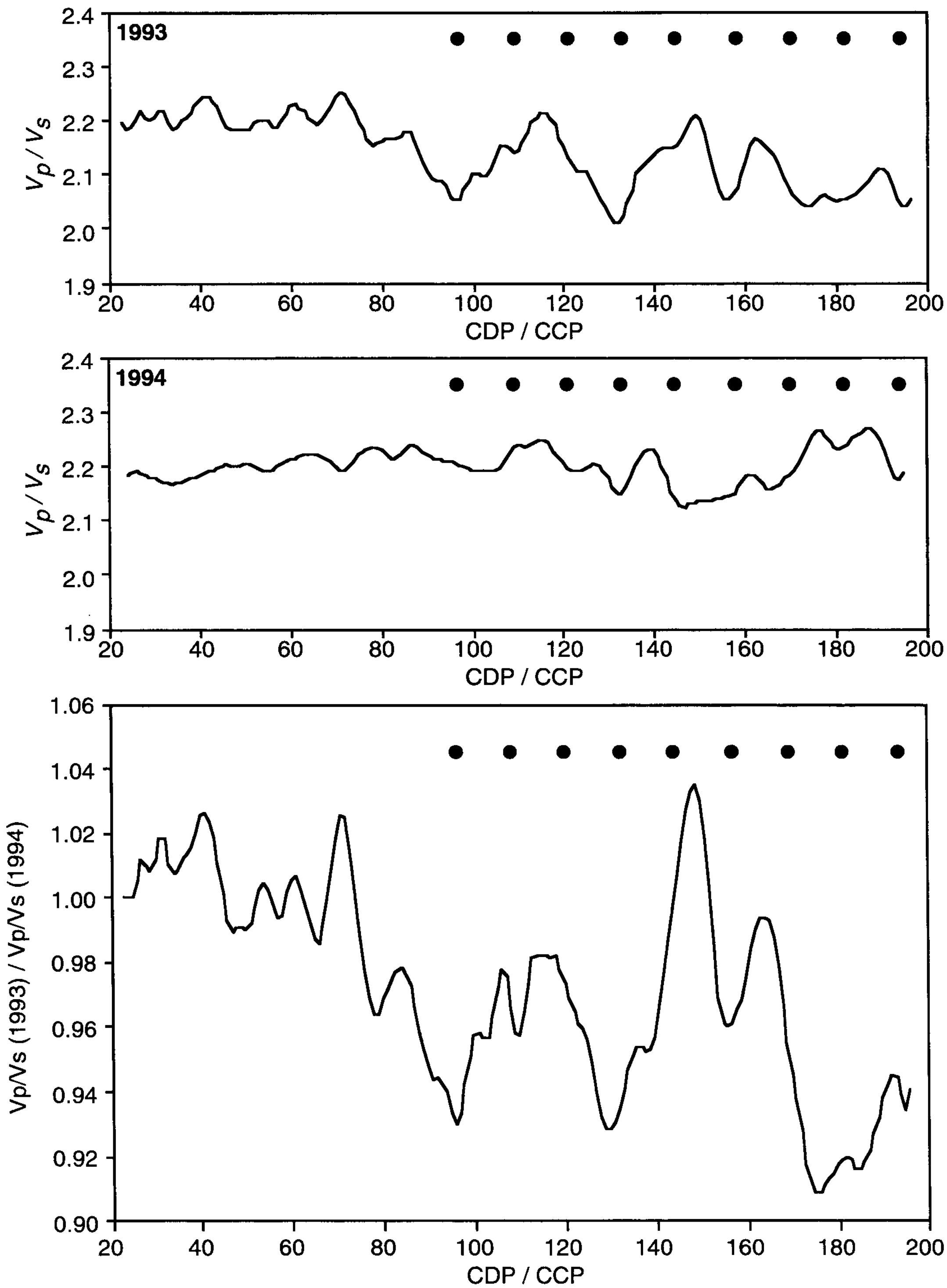

FIG. 30. Vp/Vs plots for 1993 lines, 1994 lines, and the ratio of those two. Note that the Vp/Vs value is generally lower in the unsteamed regions away from the wells (from Isaac, 1996).

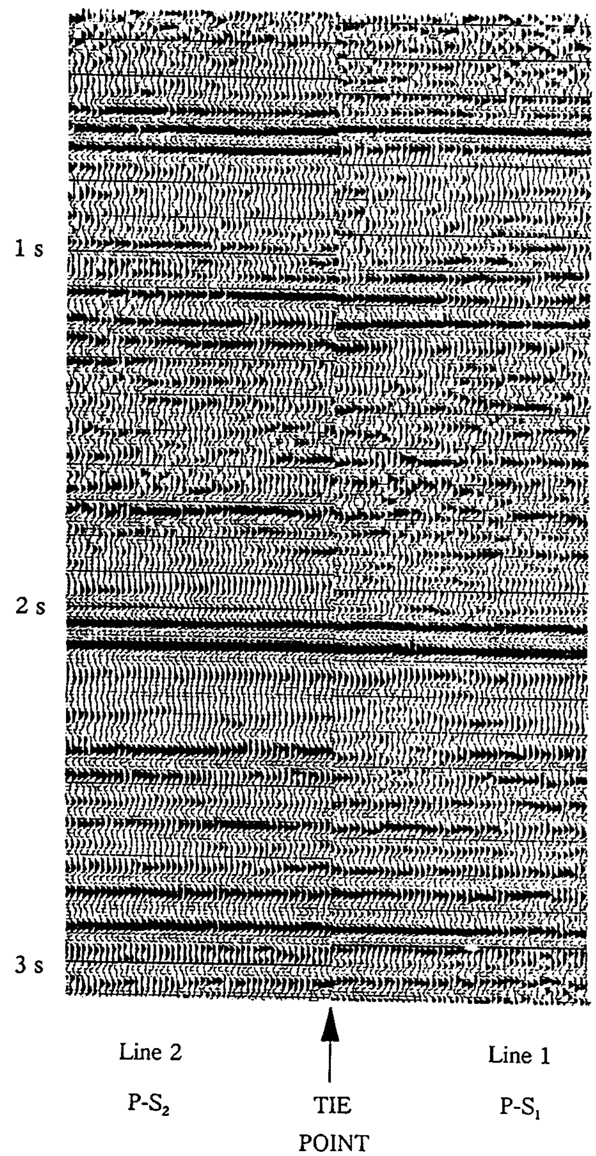

FIG. 31. P-S1 (fast direction) and P-S2 (slow direction) sections from the Willesden Green area of Alberta. No obvious anisotropy is apparent.

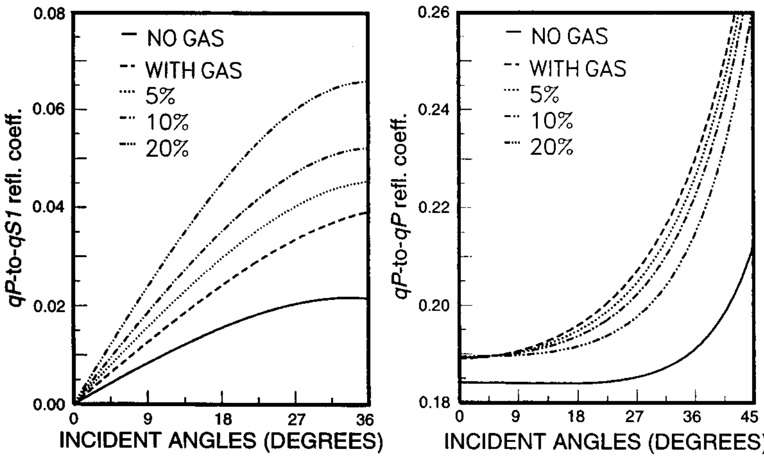

FIG. 32. Theoretical modeling for gas-saturated fractured material indicating that anisotropy may have a large effect on the P-S amplitudes (from Li et al., 1996).

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